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An Investigation into the Effects of Water Quality on Coal Flotation Performance

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***Abstract* -** In this paper, the effects of water quality on the flotation performance of bituminous coal were investigated focussing on dissolved ions. Water was synthesised to simulate process water from coal processing plants. To evaluate the effects of these ions, a series of 32 flotations tests were conducted using the synthesized process water. The ions investigated were Ca^{2+}, Mg^{2+}, Cl^{-}, SO_4^{2-}, Fe^{2+}, NO_3^{-} and the pH. Analysis of results from the laboratory tests revealed that the ion that has the most effect on the flotation performance is Cl. Higher concentrations of Cl^{-} (160 to 200 mg/l) increases the % combustible recovery. The pH was observed to be directly proportional to the % combustible recovery while Ca^{2+} and Fe^{2+} were observed to be inversely proportional. To achieve high % combustible recoveries, the optimum conditions are 24 mg/l Ca^{2+}, 39 mg/l Mg^{2+}, 200 mg/l Cl^{-}, 0 mg/l SO_4^{2-}, 0.06 mg/l Fe^{2+}, 40 mg/l NO_3^{-}, and a pH of 7.92. The most significant variable that affects the % combustible recovery is the pH, followed by Cl^{-}, NO_3^{-}, Mg^{2+}, SO_4^{2-}, Fe^{2+}, Ca^{2+} concentrations in that order.

***Keywords*:** Coal, Flotation, Water quality, Synthesized water, Optimisation

1. Introduction

The mineral processing industry uses water in most of its operations. Froth flotation process is one of the most successful concentration methods in mineral processing. It consumes a huge amount of water, e.g., flotation of 1 ton of ore usually requires 3~7 tons of water [1]. It can be widely acknowledged that water is the most essential compound that influences our everyday lives. It is crucial for environmental management and for sustainable development. Currently, there is an immense shortage of fresh water, which is possibly due to the population increment, industrialization, urbanization, and vigorous agricultural activities [2]. Most mineral processing operations have already started assessing and implementing different ways to conserve and manage water resources, bringing about sustainability benefits as well as cost effectiveness [3]. Hence, to reduce their freshwater usage, coal preparation plants have developed water usage strategies, with the most common one being the recycling of process water. The utilization of recycled process water has been the subject of extensive investigation; however, in flotation, recycling water can negatively impact mineral separation. The content of inorganic elements (suspended matter, calcium, magnesium, Fe, sulphite, sulphate, etc.), as well as organic reagents (frothers, collectors, depressants), accumulates and subsequently impacts the flotation performance [5]. From the economic perspective, using processed water minimizes the amount of fresh water required and transportation costs. Fresh water can be very expensive in areas that are arid or semi-arid. From a social perspective, recycling water reduces water discharged to the environment and there will be freshwater available for other uses [4].

According to literature, the presence of certain ions often reduces the hydrophobicity of the coal surface, raising the electrostatic charge; and vice versa [6]. Since it has been shown that flotation recovery is greatest at the isoelectric point (IEP) of the coal, whenever the surface charge is reduced, flotation recovery should be improved (as in the presence of certain ions). Additionally, the compression of the electrical double layer brought on by the injection of electrolytes reduces the stability of the hydrated layer at the coal surface. The hydrated layer is hence more readily torn by bubble contact, increasing floatability. Studies have shown that the pyrite oxidation products (Fe^{2+}, Fe^{3+}, and SO^{2-}) have an impact on coal flotation and are linked to a slight coal depression [6]. It has been shown that several salts operate as a frother by preventing bubble convergence. However, there are observable differences between inorganic substances and frothers. For instance, frothers prevent bubble amalgamation by reducing the surface tensile strength of the air bubble, but inorganic salts frequently increase it. At low salt concentrations, frothers also prevent coalescence, but high salt concentrations are necessary to significantly alter it [7].

There are a fair number of studies done on the effects of water quality on the flotation process but not specifically on the flotation of coal. Not enough studies are done on other water types except saline water and bore water and these do not give the effects of the individual ions on the flotation performance. This paper seeks to investigate the effects of the individual ions in water on coal flotation performance.

2. Materials and Methods

2.1. Materials

To study the effect of water quality on the flotation performance of coal, a bituminous coal sample from Mpumalanga Province, South Africa was used. Laboratory synthesized water was used for the flotation experiments. Reagents used for the flotation experiments were diesel oil as a collector, and Methyl Isobutyl Carbinol (MIBC) as frother sourced from Betachem, South Africa. For pH regulation, Nitric acid and Lime of AR grade were used.

2.2. Methods

The following ions were used to study the effects of water quality on the flotation performance of coal: Ca^{2+}, Mg^{2+}, Cl^{-}, SO_4^{2-}, Fe^{2+}, NO_3^{-} concentration and the pH. Based on information from the literature and results of preliminary experiments, these parameters and their respective ranges of values were selected [5]. To simulate the composition of process water from coal plants ions were added to the University of Johannesburg, Doornfontein Campus tap water.

Flotation tests were carried out on a representative sample of coal. 20kg of the sample was used. The entire sample was first crushed using a roll crusher. The product was manually screened using a 2mm sieve. The +2mm size fraction was then milled using a rod mill to obtain an entire sample of -2mm. The 20kg sample was then blended, and the final blended sample was split into two 10kg samples using the Jones riffle splitter. The 10kg samples were then further split into 1kg samples using a spinning riffler. The feed size for the flotation experiment was 80% passing 205µm. To create the necessary size fraction for use as the feed to the flotation cell, a milling curve was first generated to estimate the milling time. The milling time was then determined to be 55 minutes for a 1kg sample using a rod mill.

X - ray fluorescence (XRF), X-ray diffraction (XRD), sulfur analysis, calorific value testing, and proximate analysis are the characterisation techniques that were employed to characterise the coal feed sample.

2.3. Design of flotation experiments

The operating conditions of the flotation experiments were generated using the Taguchi optimization tool to evaluate the impact of water quality on the flotation of coal [8]. With the help of this tool, it is possible to evaluate several parameters at once using the fewest possible tests. A mixed level approach was used. 7 factors were investigated, and the design generated 32 runs. Table 1 below gives the flotation conditions per run of the experiments.

Table 1: Taguchi design of flotation experiments

Run Order	pH	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Cl^{-} (mg/L)	SO_4^{2-} (mg/L)	Fe^{2+} (mg/L)	NO_3^{-} (mg/L)
1	2,48	24	20	20	0	0,06	0
2	2,48	24	39	80	550	15,33	20
3	2,48	24	58	160	780	45,69	40
4	2,48	24	79	200	1122	73,4	60
5	2,48	120	20	20	550	15,33	40
6	2,48	120	39	80	0	0,06	60
7	2,48	120	58	160	1122	73,4	0

8	2,48	120	79	200	780	45,69	20
9	2,48	360	20	80	780	73,4	0
10	2,48	360	39	20	1122	45,69	20
11	2,48	360	58	200	0	15,33	40
12	2,48	360	79	160	550	0,06	60
13	2,48	668	20	80	1122	45,69	40
14	2,48	668	39	20	780	73,4	60
15	2,48	668	58	200	550	0,06	0
16	2,48	668	79	160	0	15,33	20
17	7,92	24	20	200	0	73,4	20
18	7,92	24	39	160	550	45,69	0
19	7,92	24	58	80	780	15,33	60
20	7,92	24	79	20	1122	0,06	40
21	7,92	120	20	200	550	45,69	60
22	7,92	120	39	160	0	73,4	40
23	7,92	120	58	80	1122	0,06	20
24	7,92	120	79	20	780	15,33	0
25	7,92	360	20	160	780	0,06	20
26	7,92	360	39	200	1122	15,33	0
27	7,92	360	58	20	0	45,69	60
28	7,92	360	79	80	550	73,4	40
29	7,92	668	20	160	1122	15,33	60
30	7,92	668	39	200	780	0,06	40
31	7,92	668	58	20	550	73,4	20
32	7,92	668	79	80	0	45,69	0

2.4. Flotation Experiments

The batch flotation tests were carried out using a 1.5 L capacity Denver flotation cell. For each run, 500g of coal sample (P80 passing 205µm) was added with the different synthesized process water according to Table 1. The coal pulp was conditioned for 3 minutes before adding reagents. The collector was then added, and the pulp was conditioned for 1 minute before adding the frother. The frother was added and the pulp was conditioned for a further 3 minutes. The impeller rotation speed was kept at 1200rpm. Frother collection was done at 10 second intervals for 5 minutes for each test. Reagents used are Diesel oil (or kerosene) and Methyl Isobutyl Carbinol (MIBC) as a collector and frother respectively. Dosage used for collector was 0.045kg/ton and 0.089kg/ton (4 drops) for frother. Flotation products were dried and weighed for analysis.

2.5.Analysis of flotation results: Signal-to-noise ratio analysis

Signal-to-Noise ratios (S/N) are log functions that are derived from "ORTHOGONAL ARRAY" studies. These studies have significantly lower "variance" when the control parameters are adjusted to their "optimal" values [9]. Dependent on

$$-10 * \log\left(\sum \frac{(\frac{1}{y^2})}{n}\right) \quad (1)$$

$$-10 * \log\left(\sum \frac{Y^2}{n}\right) \quad (2)$$

what the response variable is hoping to achieve, Eqns. (1) and (2) were used. For the % combustible recovery response, Eqn. 1, larger is better (S/N) was applicable, whereas Eqn. 2, smaller is better (S/N) was applicable for the % ash.

3. Results and Discussion

3.1.Characterisation of the as received coal sample

The sample's elemental analysis was examined using XRF, and the findings are presented in Table 2. Al and Si are in high quantities in the coal sample. Such elemental composition is mostly connected to minerals like clay (kaolinite), quartz, and ilmenite, and these are the most prevalent in coal from South Africa [8].

Table 2: Elemental composition of coal feed sample

Element	Si	Al	Fe	Ca	S	Ti	K	C
%Weight	5.57	3.35	0.84	0.72	0.31	0.21	0.20	78

Figure 1 shows XRD results used to identify the various mineral phases that were contained in the coal sample. Kaolinite ($Al_2Si_2O_5(OH)_4$), Quartz (SiO_2), Fayalite (Mg0.075Fe1.791Mn0.134(SiO_4)), Gypsum (Ca (SO_4)(H_2O)$_2$), Pyrite (FeS_2) and Chalcopyrite ($CuFeS_2$) are the minerals found in the coal sample. These mineral phases correspond with the XRF findings in Table 2. The sulphur content and Calorific Value (CV) of the coal sample was found to be 0.43% and 19.57MJ/kg respectively. From the proximate analysis conducted, the ash, moisture, volatile matter, and fixed carbon content were obtained as 33.69, 2.28, 24.20 and 39.83% respectively confirming that it is a bituminous coal.

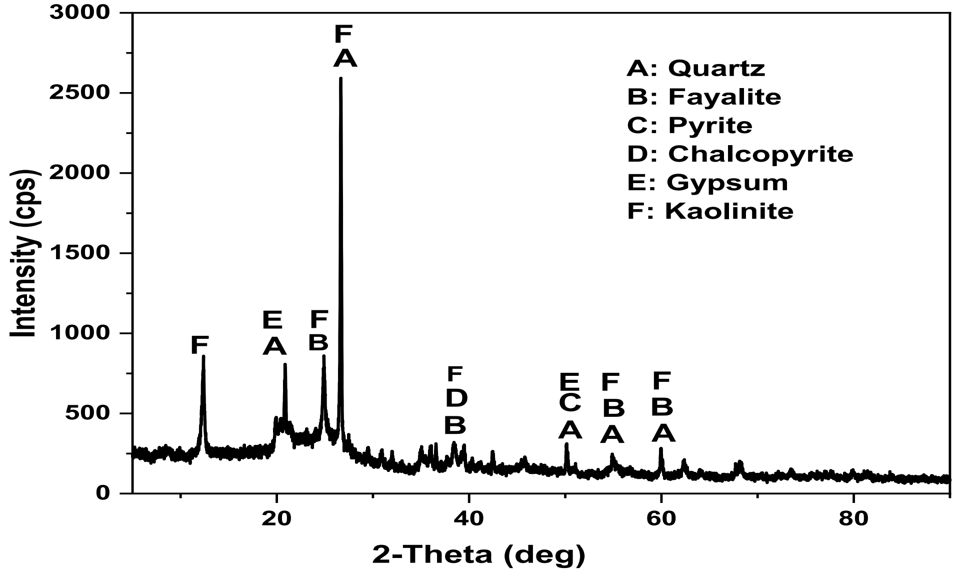

Fig. 1: Mineralogical composition of coal feed sample

3.2. Flotation experiments results

32 runs of flotation experiments were carried out using a 1.5l Denver cell. To obtain the ash %, the flotation concentrates were put in a muffle furnace and the results are shown in Table 3. From the results, it is observed that the parameters being investigated has minimal effects on the ash % hence combustible recovery was used as a response for Taguchi analysis on the minitab software.

The pH was observed to be directly proportional to the % combustible recovery while Ca^{2+} and Fe^{2+} were observed to be inversely proportional. Increasing the concentration of Mg^{2+} from 20 to 39mg/l increases the % combustible recovery and a further increase from 39 to 79 mg/l decreases the % combustible recovery. An increase in the concentration of Cl- from 20 to 80 mg/l and from 160 to 200 mg/l is observed to increase the % combustible recovery, however an increase from 80 to 160 mg/l causes it to decrease. Increasing the concentration of SO_4^{2-} from 0 to 780mg/l decreases the % combustible recovery and a further increase from 780 to 1122 mg/l increases the % combustible recovery. The % combustible recovery decreases with the increase in concentration of NO_3^- from 0 to 20 mg/l and from 40 to 60 mg/l but decreases at a concentration increase from 20 to 40 mg/l.

Table 3: Coal flotation experiment results

Sample #	Yield %Weight	%Ash	% Combustible recovery
1	8,46	27,54	9,24
2	8,3	29,64	8,81
3	8,36	28,39	9,03
4	8,04	28,68	8,65
5	8,64	28,38	9,33
6	10,26	28,47	11,07
7	7,48	29,05	8,00
8	7,94	28,60	8,55
9	8,42	29,79	8,92
10	10,06	29,15	10,75
11	14,5	28,82	15,56
12	8,86	28,02	9,62
13	9,16	29,49	9,74
14	7,46	29,69	7,91
15	9,82	28,49	10,59
16	9,28	29,48	9,87
17	12,26	27,64	13,38
18	15,8	28,87	16,95
19	14,52	29,08	15,53
20	16,52	28,48	17,82
21	16,06	29,02	17,19
22	14,4	29,74	15,26
23	12,38	29,75	13,12
24	11,82	29,21	12,62
25	9,5	29,45	10,11
26	13,86	28,73	14,90
27	10,18	28,31	11,01
28	11,32	29,58	12,02
29	10	28,52	10,78
30	15,02	29,10	16,06
31	12,76	29,03	13,66
32	11,94	28,56	12,86

The optimal conditions that would obtain the highest % combustible recovery in the process of coal flotation were identified using the signal to noise ratio, and the findings are shown in Table 4 and Figure 2. The highest % combustible recovery can be obtained at a pH of 7.92, 24 mg/l Ca^{2+}, 39 mg/l Mg^{2+}, 200 mg/l Cl^{-}, 0 mg/l SO_4^{2-}, 0.06 mg/l Fe^{2+}, and 40 mg/l NO_3^{-}. Table 4 below also show the level of significance of the different parameters. The most significant variable that affects % combustible recovery is the pH, followed by Cl^{-}, NO_3^{-}, Mg^{2+}, SO_4^{2-}, Fe^{2+}, Ca^{2+}, in that order.

Table 4: Response Table for Signal to Noise Ratios (% combustible recovery)

Larger is better							
Level	pH	Ca^{2+}	Mg^{2+}	Cl^{-}	SO_4^{2-}	Fe^{2+}	NO_3^{-}
1	19,64	21,5	20,68	20,99	21,64	21,49	21,14
2	22,77	21,22	21,78	21,07	21,51	21,5	20,72
3		21,14	21,41	20,72	20,6	21,31	22,07
4		20,97	20,97	22,07	21,09	20,54	20,91
Delta	3,13	0,53	1,09	1,35	1,05	0,96	1,35
Rank	1	7	4	2	5	6	3

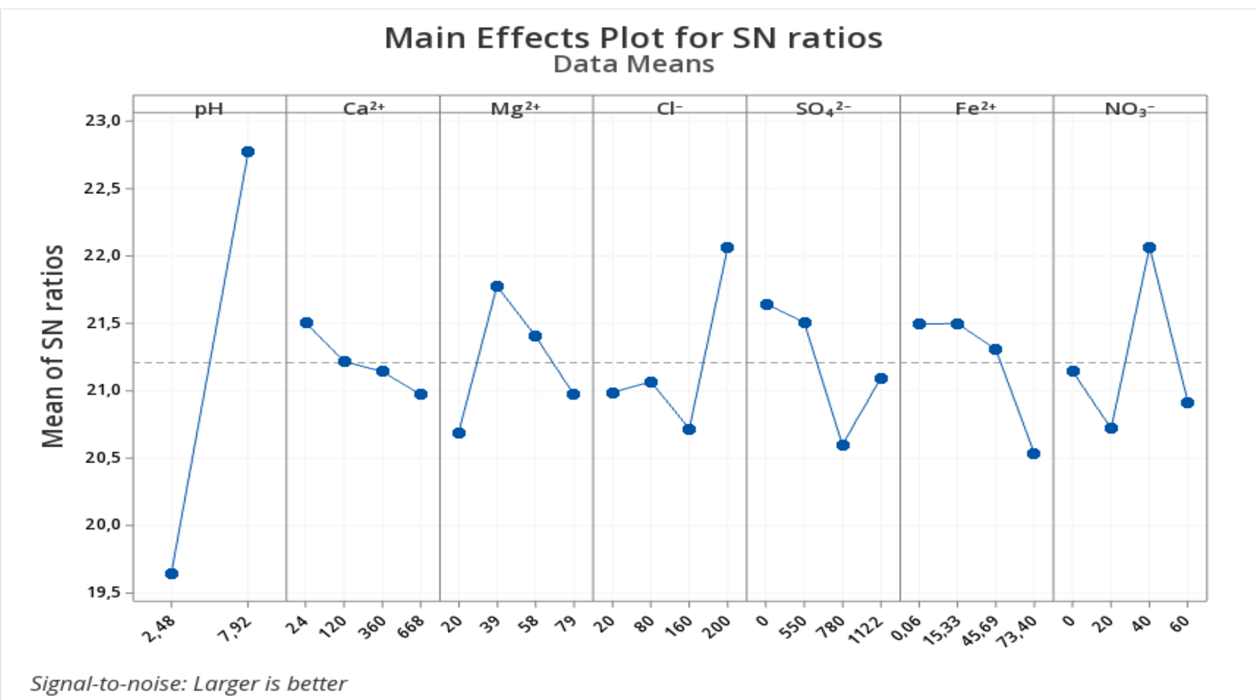

Fig. 2: Signal to noise analysis for % combustible recovery

4. Conclusion

The work presented in this paper shows strong evidence that water quality affects the flotation performance of bituminous coal. The mineralogical studies done on the coal sample revealed that major mineral phase in the coal sample Kaolinite ($Al_2Si_2O_5(OH)_4$), Quartz (SiO_2), Fayalite (Mg0.075Fe1.791Mn0.134(SiO_4)), Gypsum (Ca $(SO_4)(H_2O)_2$), (FeS_2) and Chalcopyrite ($CuFeS_2$). The flotation experiments results indicated that ions present in flotation water plays important role in flotation performance. Water can be successfully recircled in coal flotation plants thereby reducing the pressure on freshwater demand. Ions present in recirculated water has minimum effect on ash content of the processed ore, however, they affect the combustible recovery. The most significant variable that affects the % combustible recovery is the pH, followed by Cl^-, NO_3^-, Mg^{2+}, SO_4^{2-}, Fe^{2+}, Ca^{2+} concentrations in that order.

The design of experiments methodology conducted revealed that the optimum conditions for the flotation of coal using synthetic water in a 1.5L Denver cell are 24 mg/l Ca^{2+}, 39 mg/l Mg^{2+}, 200 mg/l Cl^-, 0 mg/l SO_4^{2-}, 0.06 mg/l Fe^{2+}, 40 mg/l NO_3^-, and a pH of 7.92. Thus, water recirculation has great potential in coal flotation plants.

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